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Mat. Res. Soc. Symp. Proc. Vol. 674 © 2001 Materials Research Society

Stability of Magnetic States in Patterned Materials

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ABSTRACT

The stability of the individual elements of a two-dimensional (2D) regular array of single domain particles is investigated. The variance in the statistical distribution of up- and down switching fields of the elements leads to premature switching for the low coercivity particles, and incomplete overwriting for the high end of the distribution. The distribution of the interaction fields from surrounding elements on a 2D array depends the saturation magnetization of the elements, their packing density, and the recorded information. The non-ellipsoidal shape of the elements leads to reduced switching fields as a result of non-collinear magnetization around the corners and edges. The thermal stability of 2D arrays, switching by (incoherent) rotation of the magnetization, is enhanced compared to bulk/contiguous media, due to the lack of low energy barrier domain wall motion processes. However due to the fast decrease of the anisotropy, stability at elevated temperatures is still a problem. Experimental data for a model 2D square array of single crystalline, strongly uniaxial, single domain garnet particles illustrate the effects on stability of statistics, shape, and thermal excitation.

INTRODUCTION

The interest in regular two-dimensional (2D) arrays of small magnetic particles is motivated by their potential as the next generation of high density magnetic recording media. The stability of the magnetic states of a 2D patterned magnetic system is an important practical problem with interesting fundamental aspects. The stability of the magnetic state of the individual *elements* and the *system*, as a whole, is determined by material parameters, the statistical distribution of the se parameters, shape and size of the elements, geometry of the array, and by the reversal mode.

The shape of the elements depends on the technology of preparation, it can be elliptical [1], or flat rectangular [2], or even conical [3]. The elements (bits in recording) should have two stable magnetic states, separated by an energy barrier, high enough to prevent erroneous switching, but low enough to make (over)writing possible. The easy direction can be either in-plane, or normal to the plane of the array. Perpendicular recording mode is preferred because of higher packing density. The elements of a 2D array are single domain particles. Ideal single domain particles would switch by coherent rotation, similar to the Stoner–Wohlfarth mode [4]. However, although the elements on the 2D arrays do not have any domain walls, the magnetization state is not uniform due to the presence of corners and edges. As a result, the switching mode is of incoherent rotation. Any interaction between the elements will influence the switching field. The elements are separated by nonmagnetic areas, thus the interaction between them is purely magnetostatic, and it depends on the shape, the separation between the elements, and the saturation magnetization.

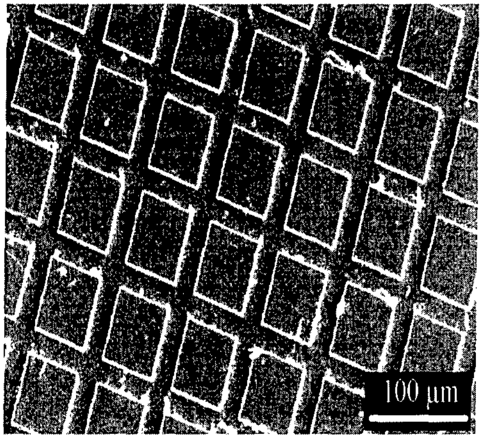


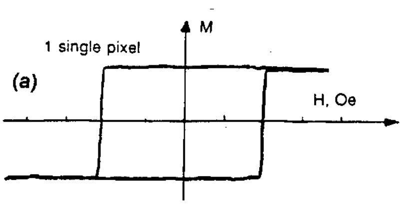
Figure 1. Scanning electron microscope (SEM) photo of a part of an epitaxial garnet wafer with the 2D square array of 40 μm x 40 μm x 3 μm particles (Courtesy of Zofia Vertesy, HAS, Budapest, Hungary).

Assuming a modest 10 Gb/cm^2 recording density, the center-to-center distance between adjacent bits is about 100 nm, including the separating "groove". A 100 Gb "disk" of this medium has an area of about 10 cm^2. For flawless operation, it is required that all the elements behave the same way. The most critical characteristics of the elements is the switching field H_{sw}, because it is very sensitive to many parameters of the system, including magnetization, anisotropy, array geometry, shape, size, defects, stress, temperature, etc. The major technological challenge for recording on 2D arrays of small particles is how to keep the switching field distribution for 10^{11} particles as narrow as it is required by the recording system? One of the main potential problems lies in the statistical distribution of the parameters of the elements on the array. The lowest switching fields will cause bit errors, while the high end of the distribution will prevent (over)writing.

In the following, the role of the statistical distribution of the properties of the elements, geometrical (shape and size) effects, interaction effects between the elements, switching modes, and temporal and thermal effects on system stability will be in examined. These effects are demonstrated on a model system of a 2D array of single crystal, single domain garnet particles.

EXPERIMENTS

Two-dimensional square arrays of 40 μm to 60 μm square, 3 μm thick garnet particles of substituted $Y_3Fe_5O_{12}$ (YIG) were etched from an epitaxially grown single crystalline film to study the magnetization process of a system of magnetically small, highly uniaxial, single domain magnetic particles. The separation between particles is about 1/3 of the lateral dimension. Figure 1. shows a detail of the photolithographed and etched LPE garnet wafer with the 2D square array of 40 μm x 40 μm x 3 μm particles.



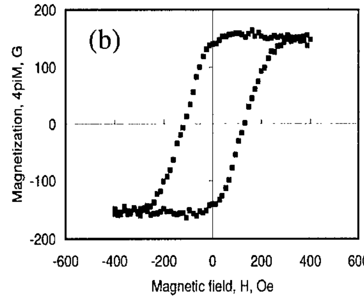


Figure 2. Hysteresis loop of an individual particle of Fig. 1., measured magnetooptically (a), and major hysteresis loop of about 3,000 particles, measured at T=50º C in a VSM (b).

Although the physical size of these garnet particles is relatively large, they satisfy the requirements of magnetic smallness: they are single domain due to a very strong uniaxial anisotropy, $H_k = 2.2$ kOe, combined with a very low magnetization, $4\pi M_s = 160$ G, resulting in a uniaxiality of $Q = H_u / 4\pi M_s \geq 10$. The easy direction of the magnetization is perpendicular to the surface of the particles. Each particle has only two stable states of the magnetization, "up" and "down". The hysteresis loop of the individual particles is rectangular, and the squareness of the major hysteresis loop of thousands of particles $S = M_r/M_s = 1$. The coercivity along the major hysteresis loop at room temperature is $H_c = 285$ Oe.

The epitaxial garnet films are of extremely high quality single crystals, and as a result, it is expected that interactions with defects do not influence the magnetization process. Another advantage of this system is its optical transparency and high magnetooptical activity. Individual hysteresis loops of hundreds of particles, and major and minor loops of assemblies of particles were measured in an optical magnetometer, with optoelectrical detection and simultaneous visual observation. Statistics of the switching fields, coercivities, and interaction fields were determined from the measured data. Mean values for over 3,000 particles (5x5 mm^2 samples) were measured by a VSM [5].

DISCUSSION

Statistical stability

Coercivity distribution

For an ensemble of a large number of particles, the statistical distribution of properties is very important. Without considering the standard deviation, the mean values for magnetic properties, geometry, interactions, can be misleading, of these quantities. The weakest link of a system is determined not by mean values of significant parameters, but their variance. The

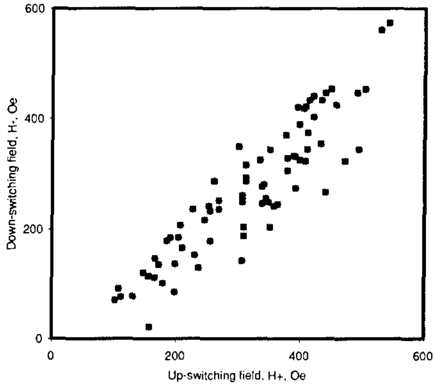


Figure 3. Measured distribution of the up- and down-switching fields H^+ and H^- of individual particles on the 2D array.

statistical distribution of the magnetic characteristics of individual particles was measured on the model system of single domain garnet particles. Figure 2. shows a hysteresis loop for a single particle, and the major hysteresis loop for thousands of particles. The up- and down switching fields (H^+ and H^-) of individual particles were determined from the individual hysteresis loops of over 200 individual particles, resulting in the switching field distribution, shown in Figure 3.

This 2D system of small particles can serve as a nearly ideal system for Preisach hysteresis models [5-7]. The Preisach model assumes that the major hysteresis loop is originating in the statistics of switching of individual particles, each characterized by a shifted rectangular hysteresis loop. The width of each individual loop is the measure of the coercivity of the given particle, while the shift is due to the interaction with the surrounding particles. The coercivity of individual particles is the halfwidth of the hysteresis loop:

$$H_c=(H^+ + H^-)/2 \tag{1}$$

The measured up- and down switching field data can be converted into a coercivity-interaction field plot, where the distribution of both can be clearly seen, as shown in Fig.4. The measured switching fields span a surprisingly broad range of about 600 Oe. The distribution of coercivities is Gaussian with H_c = (288 ± 112) Oe. The mean value corresponds to the major loop coercivity of a large number of particles. The standard deviation of H_c, σ_c = 112 Oe reflects the range of the strength of the defects, contributing to the coercivity. However, according to the Gaussian distribution, the probability to find H_c values at $3\sigma_c$ is still finite. As a result, there will be particles switching too early, at very low fields, and particles at the high end of the H_c distribution, resisting switching within the nominal field of the device operation.

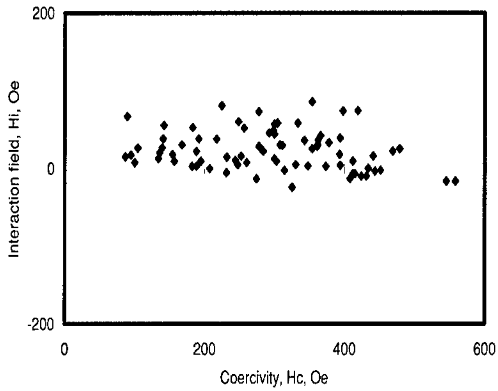


Figure 4. Distribution of coercivities, H_c and interaction fields, H_i of individual particles, calculated from the data of Fig. 3.

Interaction field distribution

The second contribution to switching field distribution originates in the *interaction fields, H_i*, between the particles, manifested in the shift of the individual hysteresis loops by the effective field from the neighbors:

$$H_i = (H^+ - H^-)/2. \qquad (2)$$

The shift of the hysteresis loops of individual particles is due to the interaction with the surrounding particles. This interaction is entirely magnetostatic, and it arises from the "demagnetizing" or "magnetizing" effects of the neighbors. The average interaction field for the data in Fig. 3 and Fig. 4 is H_i=23.4 Oe, with a standard deviation of σ_i=25.2 Oe [8-10]. For a perpendicular 2D medium the interaction field differs from the usual 3D particulate material case. Depending on the state of the neighbors of the actual particle to be switched (i.e. a bit in recording), the interactions can be "magnetizing" or "demagnetizing", causing switching at much lower or higher fields than the coercivity of the particle. For example, a central particle experiences an effective field of

$$\boldsymbol{H}_{eff} = \boldsymbol{H}_{appl} + \boldsymbol{H}_i, \qquad (3)$$

coming from the applied bias field $\boldsymbol{H}_{appl}$ and the interaction field, $\boldsymbol{H}_i = \Sigma \boldsymbol{H}_D$. The interaction field, in first approximation, is the *vector* sum of the demagnetizing fields from neighbors. This field, $\boldsymbol{H}_D = -N_{zz}\boldsymbol{M}_s$ can be very large for a high magnetization medium, and for high density (close) packing of particles. This field has been calculated by us previously by micromagnetic methods. The interaction field at a given particle, originating from all the other particles, is given by

$$\boldsymbol{H}_i = 4\pi \boldsymbol{M}_s N_{zz} \qquad (4)$$

where

$$N_{zz} = \Sigma\Sigma D_{zz}(i, j) \qquad (5)$$

summing up the interactions at each point of the 2D system with all other points. The sign of $D_{zz}(i, j)$ is determined by the state of particle j. In fact, N_{zz} corresponds to the usual demagnetizing tensor element.The measured up-switching field of a particle is equal to:

$$H^{+} = H_{c0} - H_i \qquad (6)$$

where H_{c0} is the coercivity without interactions [11, 12]. It was shown that in the calculations the interactions with the surrounding particles can be truncated at the 3rd coordination shell. The effect of the state of the neighbors was measured, and micromagnetically calculated for 25 particles (embedded in a 9x9 array), showing that when all the 24 neighbors are switched "up", in other words, no neighbors are in the "down" state, $H_i = 86$ Oe for $H^+ = 398$ Oe, resulting in $H_{c0}=312$ Oe for that particle, in very good agreement with experiments. To illustrate the worst case scenario, let's assume 4 nearest neighbors of a central particle, and $N_{zz}=1$. Then, in the worst case, when all the neighbors are magnetized in the same direction as the central particle, $\boldsymbol{H_{eff}}$ can change from $(H_{appl} - 4*4\pi M_s)$ to $(H_{appl}+4*4\pi M_s)$, i.e. by $|8*4\pi M_s|$ upon inverting the magnetization of the central particle. On a square array, the interaction is the strongest between the corners of neighboring elements. These effects can lead in one case to premature switching, in the other, to difficulty of (over)writing, thus significantly affecting the stability of digital information in 2D recording media. At the same time, around the corners, the magnetization is canted, and large in-plane interaction field component exists, acting on the neighbors, further reducing the switching field. Thus, the interaction field with the neighbors depends on the shape, density, and magnetization state of the elements i.e. the total magnetization of the array, what leads to the increase of the variance of the interaction field. This field is proportional to the saturation magnetization of the material. High M_s is preferred for a high read signal. This taken together with the requirement for high packing density results in a high interaction field. High interaction field means low stability of the magnetic state, i.e. the stability of the information on a 2D array depends on the information itself.

Switching instability due to shape effects

For perpendicular recording the most important demagnetizing tensor component is N_{zz}. For finite aspect ratio shapes, $N_{zz} \neq 1$, i.e. it differs from the thin film value. Due to the non-ellipsoidal shape of these particles, the *local* demagnetizing tensor elements, $N_{zz}(\mathbf{r})$ inside the particles should be taken into account and calculated numerically [13-16]. The resulting internal field and magnetization distribution $M(\mathbf{r})$ in a rectangular or cylindrical particle will be non-uniform. For a 1:1:0.1 aspect ratio particle, even in a large field, $H_{appl} = 5\pi M_s$, the magnetization will be canted at the corners and at the edges by an angle up to about 30°. The magnetization of such a particle will have a significant in-plane component. Figure 5 illustrates how the local N_{zz} values, shown across the centerline of a rectangular particle, deviate from the thin film value of 1 for different aspect ratios. It is clearly seen that even for an aspect ratio of thickness/lateral size=0.01, the decrease of N_{zz} around the corners is about 50%!

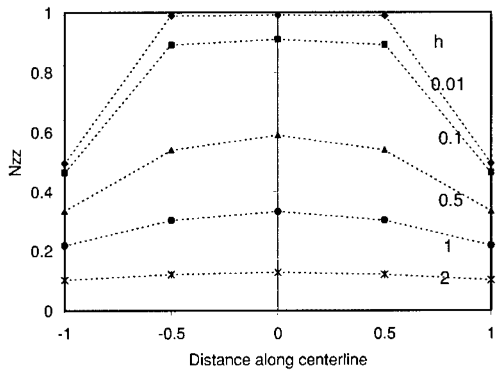


Figure 5. Shape dependence of the $N_{zz}(\boldsymbol{r})$ local demagnetizing tensor component along the centerline for unit square base columns of height $0.01 \leq h \leq 2$. The connecting lines serve only to guide the eye.

For a single domain particle, switching along the easy axis by the Stoner-Wohlfarth mode, the switching field is expected to be equal to the anisotropy field, $H_c = H_k$ [4]. However, in the case of non-ellipsoidal small particles $H_c \ll H_k$, indicating that the magnetization switching is not a uniform rotation process. Early micromagnetic calculations did show that the uniform rotation is always an idealization [17], later this became a fact of life [18]. The switching mode of these particles is by incoherent rotation. The switching field is significantly reduced. The dominant source of reduced switching field is the inhomogeneous internal field, resulting in a non-collinear magnetic structure around the corners and edges. Due to the canted magnetization, according to the switching asteroid, the switching starts much earlier, than it would be for a particle, uniformly magnetized along the particle normal. The canted moments are the seeds of switching. [19, 20]. The statistics of the interaction field with the surrounding particles, the lowered nucleation barriers at crystalline defects, also contribute to the observed switching field and its standard deviation. However, the main cause of the reduction in the switching field and of the switching instabilities is the non-uniform internal field.

Temporal and thermal stability

One of the major concerns about patterned media is the thermal and temporal instability of the information, due to the low anisotropy energy $E_K = KV$ of the small volume (V) particles with respect to the fluctuations of thermal energy [21, 22]. In continuous, or bulk magnetic materials, even in the case when the dominant mechanism of the magnetization change is rotation, domain wall (DW) motion processes are always present around the coercivity. The critical field for domain wall motion, compared to the anisotropy field for rotation, is several orders of magnitude lower. As a result, the probability of magnetization reversal by domain wall motion in continuous media is very high, especially around the coercivity of the major hysteresis loop. This gives rise to the characteristic maximum on the magnetic viscosity, $S=dM/d\ln t$ vs H, curves. It is assumed, that for materials where DW processes are excluded, as in the case of single domain

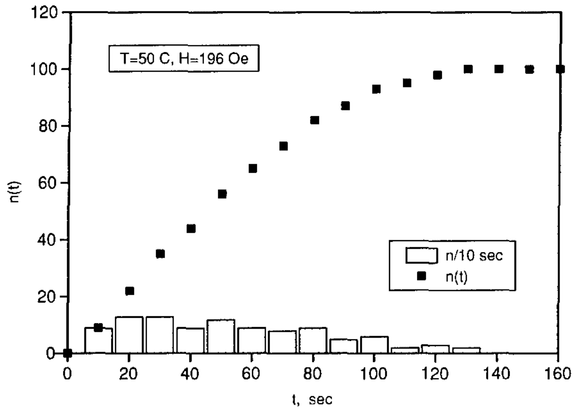


Figure 6. Rotation aftereffect for the particles on the 2D array , T=50, H=190 Oe. n/10 – the number of particles, switched in 10 sec intervals; n(t) - the total number of particles switched during t sec.

particles, this curve is more or less flat. There is still a statistical distribution of the switching fields of the particles, reflected in the shape of the $S(H)$ curve, but this distribution is much narrower than the distribution of the energy barriers for domain wall motion and rotation taken together. Therefore, lowered sensitivity of the magnetic aftereffect to the magnetic field is expected for a patterned recording medium of high anisotropy particles.

The particles in our model system of 2D arrays are thermally very stable, due to the high anisotropy field, $H_K = 2$ kG. Combined with the very low magnetization, the uniaxial anisotropy constant $K_u = 1.3*10^4$ erg/cm^3, $V = 7.5*10^{-9}$ cm^3. Thus the anisotropy barrier at room temperature $E_K \cong 10^{-4}$ erg in $H = 0$, compared to the thermal fluctuations energy of $E_T \cong 40 k_B T \cong 10^{-12}$ erg. The lowest switching field is about 100 Oe, the highest is above 500 Oe (see Fig.4). If to assume the worst case: i.e. that the barrier height H_b is lowered the most at the lowest switching field; the incoherent switching volume is not the whole particle volume, but only a 0.8 μm "rim" of the particle, where the magnetization is strongly canted (corresponding to the activation volume V_a); the applied field is H_c; the barrier height $E_K = K_u V_a (1-H/H_b)^2 = 10^{-6}$ erg, it is still several orders of magnitude higher than the thermal energy of $E_T \cong 40\ k_B T \cong 10^{-12}$ erg. This is in agreement with the experimental data, that there was no observable aftereffect on the 2D array of garnet particles at room temperature, independent of the magnetic field, applied to lower the barrier height [23].

However, upon increasing the temperature, the anisotropy barrier is lowered, the coercivity is decreasing (at $T = 50°$C $H_c = 164$ Oe; at $T = 72°$C $H_c = 128.5$ Oe); the thermal fluctuations increase, and it becomes possible to observe the rotational aftereffect. The magnetic aftereffect, i.e. the time evolution of the number of particles, switched during 10 s intervals at 50°C in H=190 Oe, is plotted in Fig.6. This plot reflects the distribution of the barrier heights of the particles. At 50°C the distribution of particle's switching time is rather even. The "best" particle, with no defects is switching the last (130 s), as it has the highest barrier. At 72°C the barriers are much lower, the switching proceeds faster, the last observed particle switches in 70 s [24]. This means for a future patterned recording medium, switching by rotation, the temporal and thermal stability at room temperature is of much less concern, than for a traditional continuous thin film, where thermal relaxation due to domain wall motion processes is significant. However, the thermal stability at elevated temperatures depends primarily on the temperature dependence of the anisotropy energy. The magnetocrystalline anisotropy is usually a strong function of the temperature, decreasing as fast as $K(T) \approx M_s(T)^3$. This means that special attention should be paid to the temperature sensitivity of the switching effects in 2D patterned media above room temperature.

CONCLUSIONS

Factors, affecting the stability of the magnetic states of the elements and the system of 2D patterned media have been investigated. Regular 2D arrays of nanosize magnetic particles, having a potential application in future extreme high density magnetic recording, are now manufactured at several laboratories. The stability of the system depends on the statistical distribution of the up- and down switching fields of individual elements of the array. The mean value of the switching fields of the elements is equal to the major loop coercivity of the system. However, the standard deviation of the switching fields depends on the local effective anisotropy fields of crystalline and manufacturing defects, leading to premature switching of the particles with strong defects, and stabilizing against overwriting the "best" particles. The unexpectedly large standard deviation of the switching field distribution is a major obstacle on the road to magnetic RAMs. Introduction of a well-defined, technologically completely reproducible 'weak point" might reduce the switching field instabilities, however, at the price of a lower average switching field.

Another factor affecting stability is the (magnetostatic) interaction between magnetically separated elements. Its mean value depends on the saturation magnetization of the system, on the total magnetization of the system with up- and down magnetized elements, and on the geometry of the separation between particles. High magnetization materials and high density increases the interaction fields. The standard deviation of the interaction field depends not only on the statistical errors in the geometry of the array, but it depends also on the total magnetization of the system. This means, that for a 2D magnetic recording medium, the stability of the recorded information depends on the information itself.

The magnetic properties of these systems depend very strongly on the shape, size, and geometry of the elements. The switching of the magnetization of non-ellipsoidal particles proceeds via incoherent rotation. The internal field and the distribution of the magnetization in these particles is strongly inhomogeneous. The switching field is significantly reduced from the idealized Stoner-Wohlfarth value. The dominant source of reduced switching field is the inhomogeneous internal field, resulting in a non-collinear magnetic structure around the corners and edges, serving as starting points for magnetization reversal, even in systems, free from manufacturing and crystalline defects.

The stability against thermal excitation depends on the details of the magnetization process. The magnetization process in film and bulk materials involves both low energy barrier domain wall motion and high energy rotational processes. However, the thermal stability of single domain particles, switching by rotation, is much higher than for a continuous medium, which has a much broader switching barrier distribution, ranging from the domain wall motion coercivity up to the anisotropy field.

Experimental data for a model system of a 2D square array of single crystalline, strongly uniaxial, single domain magnetic garnet particles illustrate the effects of statistics, shape, magnetization process, and thermal relaxation effects on the of magnetic states of the system.

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